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The Statistical Variation of Wind Turbine Fatigue Loads

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Abstract

The objective of the present investigation is to quantify the statistical variation associated with fatigue loads for wind turbines. Based on aeroelastic calculations for a 1.5 MW stall regulated wind turbine, the variation is quantified, and parameters of importance for the statistical variation are investigated.

The results illustrate that the coefficient of variation of the life time equivalent load range, for typical wind turbine load components, is of the order of magnitude 5%. This result is based on one 10 minute simulation for each of 10 wind speed intervals between 5 and 25 m/s. It is shown that the effect of mean stress level is of major importance in fatigue analysis. Furthermore, the influence of simulation length and turbulence intensity is illustrated. Finally, an estimate of the uncertainty of the life time equivalent loads is given in general terms.

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Contents

1 Introduction

The design load basis for wind turbines can be divided into two parts: A part concerning the fatigue loads and a part dealing with the ultimate extreme loads. For both parts, the load basis is usually established from aeroelastic simulations using an aeroelastic time-domain code. A central point in this method is the simulation of wind turbulence time series, where several simulation methods can be used, [2, 6]. In order to reflect the characteristics of the natural wind, the turbulence time series are simulated as stochastic fields, i.e. some random characteristics exists, which is reflected in the load simulations. The statistical variation in the extreme loads due to the random characteristics of the turbulence was investigated by Thomsen and Madsen, [5], and a method for reducing the variation was given. For the statistical variation of fatigue loads no previous work has been reported.

The statistical variation of loads is important for the assessment of the structural safety of a wind turbine. Usually, the partial safety factor method is used for handling the uncertainties involved in the determination of the design loads. A number of quantifiable uncertainties exists, however, in order to determine the total uncertainty of loads, the statistical variation must be known, too.

The objectives of the present work is to quantify the statistical variation of fatigue loads and to identify the sensitivity of this statistical variation to the main parameters involved, i.e. the wind parameters (eg. turbulence intensity) and simulation parameters (eg. simulation length).

The method to be used is based on a high number of time-domain load simulations followed by fatigue analysis of the resulting load time series. The investigation is carried out for a specific turbine, but the results – which are often given in relative terms – are believed to be general and can be used for other turbine configurations as well. If the wind turbine configuration or concept differs significantly from the one used in the investigation a similar analysis must be carried out.

The general fatigue analysis is described in Section 2 and a description of the aeroelastic code and the specific turbine used in the investigation is given in Section 3. In Section 4 the results for the fatigue impact at individual load cases – e.g. at a certain wind speed – are given and results for the total life time fatigue impact are given in Section 5. In wind turbine fatigue analysis, the influence of reduced fatigue strength caused by preloading is often ignored, potentially leading to non-conservative designs. The importance of this is ilustrated in Section 6. The two main parameters concerning the variability of fatigue loads are the simulation length and the number of simulations for each load case. This is investigated in Section 7. In Section 8, the influence of the turbulence intensity is illustrated. Finally, in Section 9 the results are summarized and expressed as uncertainties of the life time equivalent loads.

2 Preliminaries

The traditional way to assess the fatigue impact of stochastic loads is to use a counting method to establish a spectrum of ordered load ranges and associated numbers of load ranges. Usually the Rainflow counting method is applied and the result is a set of load ranges R_i and the corresponding number of load ranges n_i: $R_i(n_i)$. The number of load range levels, N, is usually 30-50, i.e. $i = 1, 2, 3, ..., N$.

2.1 The concept of fatigue damage

In order to quantify the fatigue impact, the fatigue damage is introduced. For a single load range R_i the definition of fatigue damage is:

$$d_i = \frac{1}{N_i} \tag{1}$$

where N_i is the acceptable number of load ranges from the material Wöhler curve. The basic assumption for this definition is the Palmgren-Miner linear damage rule, stating that the damage from several load ranges can be added linearly. The damage caused by a number of load ranges n_i, at the load range R_i is:

$$D_i = n_i d_i = \frac{n_i}{N_i}. \tag{2}$$

By the definition of d_i it follows that if $D_i = n_i d_i$ equals unity, fatigue failure will occur.

Assuming a linear relation between the material stress level and number of cycles in a log-log plot:

$$\log S_0 - \frac{1}{m} \log N_i = \log S_i, \tag{3}$$

or

$$N_i = \left(\frac{S_0}{S_i}\right)^m, \tag{4}$$

where S_0 is the stress corresponding to $N = 1$ (the static strength), S_i is the stress corresponding to R_i and m is the Wöhler curve exponent, the damage can be expressed in the stress level as:

$$D_i = n_i d_i = \frac{n_i}{N_i} = \frac{n_i}{\left(\frac{S_0}{S_i}\right)^m} = \frac{n_i S_i^m}{S_0^m}. \tag{5}$$

Since damage usually is used as a relative measure of the fatigue impact, this is often simplified to (neglecting S_0^m and converting to load ranges instead of stress ranges):

$$D_i = n_i d_i \propto n_i R_i^m \tag{6}$$

which now express the total relative damage from load level i. The total damage is obtained by adding the relative damage contribution, corresponding to several load ranges of different size, linearly:

$$D = \sum n_i R_i^m \tag{7}$$

2.2 The damage equivalent load

The damage is a rather fictious quantity, and it is usually more convenient to evaluate fatigue impact in more physical quantities. We now define a damage equivalent load range R_{eq} and the corresponding number of load ranges n_{eq}, which causes the same damage as the real load spectrum with several load levels, $R_i(n_i)$:

$$D = \sum n_i R_i^m = n_{\text{eq}} R_{\text{eq}}^m, \tag{8}$$

which can be expressed as

$$R_{\text{eq}} = \left(\frac{\sum n_i R_i^m}{n_{\text{eq}}} \right)^{1/m}. \tag{9}$$

This definition of the damage equivalent load range is well know in fatigue analysis and often used in wind turbine load analysis, see eg. [4].

2.3 Combination of several load cases

If several load cases, eg. different wind speeds, are to be combined, the number of load cycles in all load ranges can be added according to a prescribed probability of the different load cases. Afterwards, the life time equivalent load range can be calculated, analogous to Eq. (9). Alternatively, the life time equivalent load range can be based on the equivalent load ranges for the different load cases and integrated over all load cases.

The damage from one load case (e.g. at the 10 minute average wind speed U) is $R_{\text{eq}}(U)^m n_{\text{eq}}$. The probability of the load case is described by the probability of the wind speed $p(U)$ and the number of occurences of the load case (i.e. the number of 10 minute periods in 20 years), n_T. Integrating over all wind speeds, the total damage becomes:

$$D_L = \int R_{\text{eq}}(U)^m n_{\text{eq}} p(U) n_T \mathrm{d}U \tag{10}$$

where $R_{\text{eq}}(U)$ is the equivalent load range for the individual load cases, based on the equivalent number of load ranges, n_{eq}. $p(U)$ is the probability of the load cases, eg. a Weibull distribution of wind speeds, n_T is the number of short time periods (corresponding to one load case) in the total life time.

This total damage can be described by a life time equivalent load range L_{eq} and a corresponding life time number of ranges, $n_{\text{eq,L}}$:

$$D_L = n_{\text{eq,L}} L_{\text{eq}}^m \tag{11}$$

Then it follows that

$$L_{\text{eq}} = \left[\frac{\int R_{\text{eq}}(U)^m n_{\text{eq}} p(U) n_T \mathrm{d}U}{n_{\text{eq,L}}} \right]^{1/m} \tag{12}$$

The present investigation will primarily be based on the individual load case equivalent load (Eq. (9)) and damage (Eq. (8)) and the life time load (Eq. (12)) and associated damage (Eq. (11)).

3 Aeroelastic simulations

In order to investigate the statistical variation of simulated fatigue loads, load simulations for a specific wind turbine are used. The turbine represents the large Danish stall-regulated wind turbines, and it is believed that the results from this turbine will be typical for a wide range of large wind turbines. Main data for the turbine are given in Table 1.

Table 1. Main data for the wind turbine

Number of blades	3
Rotor diameter	64 m
Hub height	80 m
Rotational speed	17 rpm
Rated power	1.5 MW

The aeroelastic model used is the HAWC model, [3], in combination with the Mann turbulence simulation method, [2]. For five wind speeds between 5 m/s and 24 m/s a large number of simulations (100) have been carried out using different time histories of the turbulence, i.e. different seed values. The statistics of the turbulence is the same, but the time histories are different. For all simulations a turbulence intensity of 0.15 has been used and the length of the simulations are $T = 600$ s. Two sample time series for the flapwise blade bending moment at 15 m/s are illustrated in Figure 1. The resulting load time series has been analysed using the methods described in Section 2.

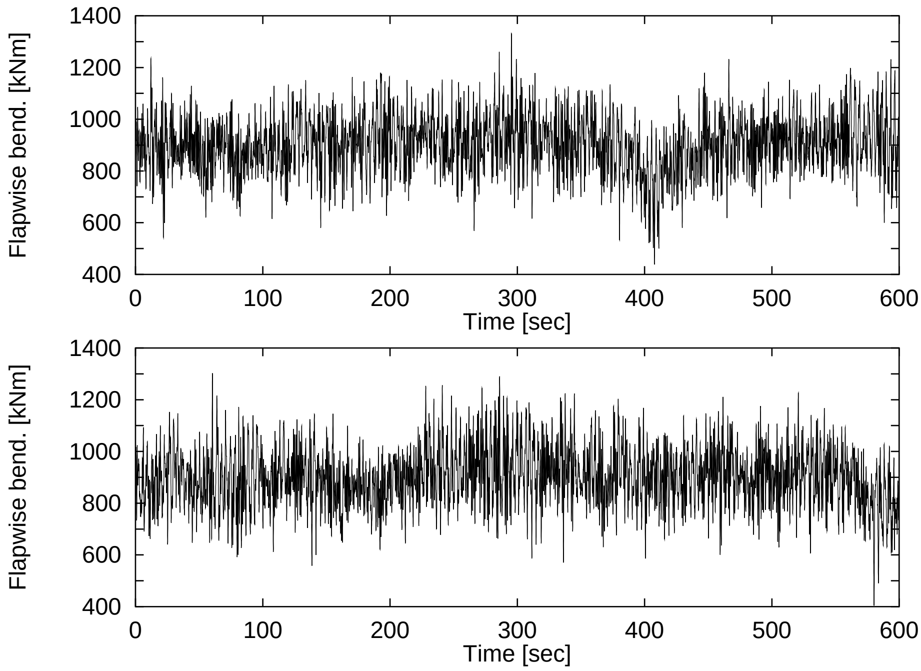

Figure 1. Sample time series of flapwise blade bending moment at U=15 m/s.

4 Characteristics of the equivalent loads

Due to the variation of the turbulence time history (seed parameter) from one simulation to another, the load time history will be different, too, Figure 1. Different load time series will result in different Rainflow counting spectra $R_i(n_i)$ and the equivalent loads representing the fatigue damage will differ as well. This statistical variation is investigated in the following using the aeroelastic calculations described in Section 3. The emphasis is given to the flapwise blade bending moment at the blade root but other loads are analyzed as well. These are the yaw and tilt moment in the tower top, the longitudinal tower bottom bending moment and the electrical power representing the torque in the main shaft. For all load components - except the flapwise bending - the Wöhler curve exponent is chosen to $m = 3$. For the flapwise bending $m = 12$. The statistical variation of the material Wöhler curves are not included in the analysis.

For the flapwise blade bending moment, the equivalent loads for all simulations at 10 m/s are illustrated in Figure 2, and it is obvious that a significant variation exists.

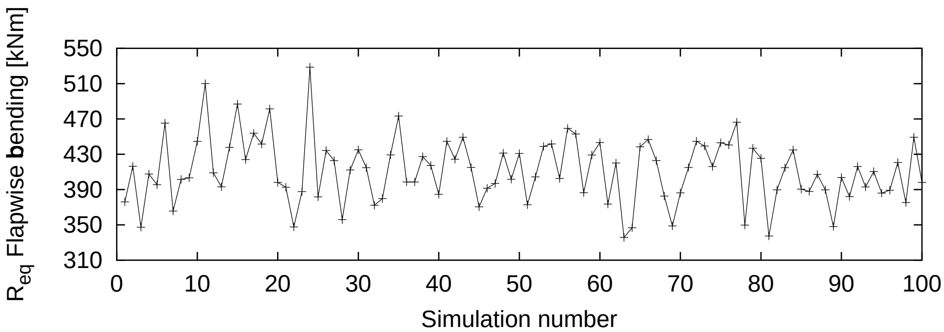

Figure 2. Calculated equivalent loads for the flapwise bending moment at 10 m/s.

In order to investigate the characteristics of the equivalent loads, the distribution of these has been calculated using the traditional method of bins. This analysis has been carried out for all load components at several wind speeds, and examples for the flapwise bending are given in Figure 3. From the histogram plots it is seen that a Gaussian distribution seems reasonable. However, the calculation of the actual histogram depends heavily on the methods of bin, e.g. on the number of bins. Thus, in order to assess the distributional functions more qualitatively, a Kolmogorov-Smirnov test has been carried out at a confidence level of 95%. The corresponding intervals are illustrated in the cumulative probability plots and it is seem that the Gaussian distribution fits well at this confidence level. It is concluded that the equivalent loads are Gaussian distributed. This is very convenient since it then can be characterized by a mean value R_{eq} and a standard deviation $\sigma(R_{\text{eq}})$.

In Table 2 the statistics of the equivalent load for all load components are given at several wind speeds. It is seen that the coefficient of variation $v_r = \sigma(R_{\text{eq}})/\bar{R}_{\text{eq}}$ decreases from 0.11-0.16 at 7 m/s to 0.04-0.05 at 24 m/s for the main part of the load components. This characteristics is different for the tower bending load, where the coefficient of variation is rather constant 0.10-0.17. The reason could be the reduced aerodynamic damping in stall causing a higher sensitivity to the characteristics of the turbulence time history.

In order to assess the relation between the variations in the equivalent moments

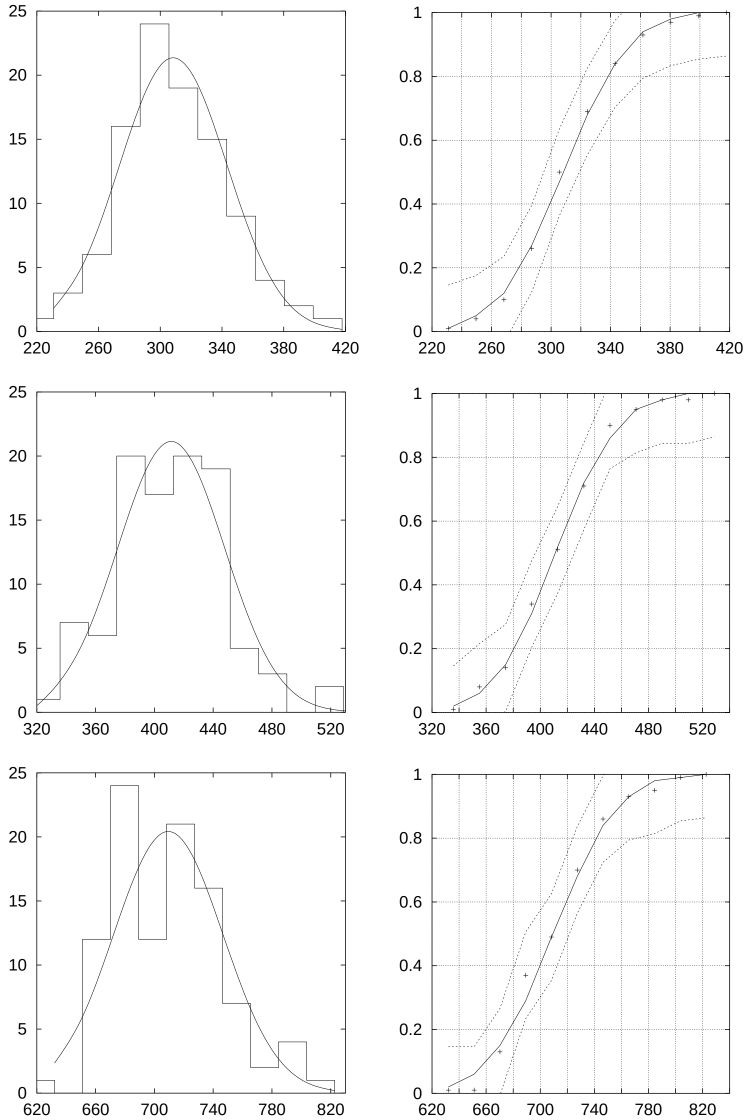

Figure 3. Histogram of probability and cumulative frequency functions of the flapwise equivalent load range at three different wind speeds. The abcissa are flapwise bending [kNm] and ordinates are probability and accumulated probability, respectively. Top: 7 m/s, middle: 10 m/s, bottom 20 m/s. The dotted lines in the cumulative frequency plots limit the 95% confidence interval based on a Kolmogorov-Smirnov test.

for the different load components, a correlational analysis has been carried out. At three different wind speeds, 10 m/s, 15 m/s and 20 m/s, the coefficient of correlation of the equivalent load range between all load components has been calculated, Table 3. At 10 m/s the equivalent loads are rather correlated, but for the higher wind speeds the coefficient of correlation reduces significantly. In particular the correlation between the flapwise equivalent load and the tower bending equivalent load is reduced, e.g. at 20 m/s the coefficient of correlation is 0.02. Thus, for the higher wind speeds it can not be assumed that a turbulence time series that causes high flapwise fatigue loads also causes high loads for the tower bending moment.

Table 2. Summary statistics of equivalent load ranges for all load signals. T =600 s, n_{eq}=600, m = 3 for all load signals except flap where m = 12. I = 0.15.

U m/s	-	Flap kNm	Power kW	Tilt kNm	Yaw kNm	Tow.B. kNm
7	$\bar{R}_{\mathrm{eq}}$	308.46	102.38	213.42	204.60	828.71
	$\sigma(R_{\mathrm{eq}})$	34.89	14.47	34.16	32.74	139.22
	v_r	0.11	0.14	0.16	0.16	0.17
10	$\bar{R}_{\mathrm{eq}}$	411.43	205.21	292.08	285.63	1511.06
	$\sigma(R_{\mathrm{eq}})$	36.39	24.05	37.92	36.54	153.19
	v_r	0.09	0.12	0.13	0.13	0.10
15	$\bar{R}_{\mathrm{eq}}$	488.96	237.48	402.39	405.76	3151.06
	$\sigma(R_{\mathrm{eq}})$	39.21	20.90	34.34	31.63	420.60
	v_r	0.08	0.09	0.09	0.08	0.13
20	$\bar{R}_{\mathrm{eq}}$	709.46	225.01	655.07	640.45	6059.41
	$\sigma(R_{\mathrm{eq}})$	37.21	12.26	34.05	31.75	907.36
	v_r	0.05	0.05	0.05	0.05	0.15
24	$\bar{R}_{\mathrm{eq}}$	828.79	236.63	749.26	739.70	7703.10
	$\sigma(R_{\mathrm{eq}})$	42.79	10.56	37.90	32.26	1139.28
	v_r	0.05	0.04	0.05	0.04	0.15

Table 3. Coefficients of correlation for the equivalent load range of different load components.

10 m/s					
	Flap	Tow.B.	Tilt	Power	Yaw
Flap	1.00				
Tow. B.	0.69	1.00			
Tilt	0.79	0.74	1.00		
Power	0.82	0.76	0.94	1.00	
Yaw	0.80	0.78	0.94	0.94	1.00
15 m/s					
	Flap	Tow.B.	Tilt	Power	Yaw
Flap	1.00				
Tow. B.	0.19	1.00			
Tilt	0.67	0.26	1.00		
Power	0.60	0.29	0.87	1.00	
Yaw	0.68	0.24	0.94	0.89	1.00
20 m/s					
	Flap	Tow.B.	Tilt	Power	Yaw
Flap	1.00				
Tow. B.	0.02	1.00			
Tilt	0.60	0.29	1.00		
Power	0.31	0.47	0.66	1.00	
Yaw	0.54	0.34	0.96	0.68	1.00

5 Accumulation of fatigue damage

In the previous section the characteristics of the equivalent loads at distinct wind speeds were described. However, for a wind turbine component the cumulative fatigue damage for all load situations during the life time must be taken into account and this integrated effect is investigated in this section. Furthermore, the variation in equivalent loads at the individual wind speeds will cause a variation in the life time loads. This integrated variation represents the total statistical variation of the fatigue loads.

The calculation of life time loads are based on Eq. (12) and the integration is substituted by a summation over 10 wind speeds between 5 m/s and 25 m/s. A Weibull distribution with parameters $A = 10$ m/s and $k = 2.0$ is assumed for the mean wind speed.

In Eq. (12) the equivalent load is constant at each wind speed. In order to account for the variation in equivalent load at each wind speed the equivalent load is now described by the Gaussian distribution identified in the previous section. Based on the 5 wind speeds used in the previous section, a polynomial fit in the mean value and standard deviation of the equivalent load is used to obtain the statistics for 10 wind speeds. The result is illustrated for the flapwise bending moment in Table 4 and Figure 4.

Table 4. Statistics of equivalent flapwise load at different wind speeds. Based on simulations with $T = 600$ seconds.

U	$\bar{R}_{\text{eq}}$	$\sigma(R_{\text{eq}})$	v_r
m/s	kNm	kNm	-
6	228.99	35.58	0.16
8	360.20	34.98	0.10
10	411.43	36.39	0.09
12	434.39	38.12	0.09
14	464.54	39.12	0.08
16	521.13	39.01	0.07
18	607.17	38.06	0.06
20	709.46	37.21	0.05
22	798.56	38.03	0.05
24	828.80	42.79	0.05

Describing the equivalent load as a distribution at each wind speed, the result of Eq. (12) will be a distribution of L_{eq}. It is not straigthforward to calculate this distribution and a Monte Carlo simulation method is therefore applied. For a large number of realizations (50.000), L_{eq} is calculated from Eq. (12) and for each wind speed the equivalent load R_{eq} is found from a Gaussian random distribution with the correct characteristics. The result is a large number of calculated life time equivalent loads which are used to identify the characteristics of the accumulated fatigue. It should be noted that this method is equivalent to using different seed values (turbulence time histories) at each wind speed.

Examples of the results are illustrated in Figures 5-6. For the life time equivalent load a Gaussian distribution fits well, while the life time damage is seen to be skew towards high values. This is due to the relatively high Wöhler curve exponent for the flapwise bending moment and the distributional function of the life time damage tends to become an extreme value type 1 distribution.

The statistics for the life time equivalent load and damage are given in Table 5 for all load components. The coefficient of variation of the life time equivalent

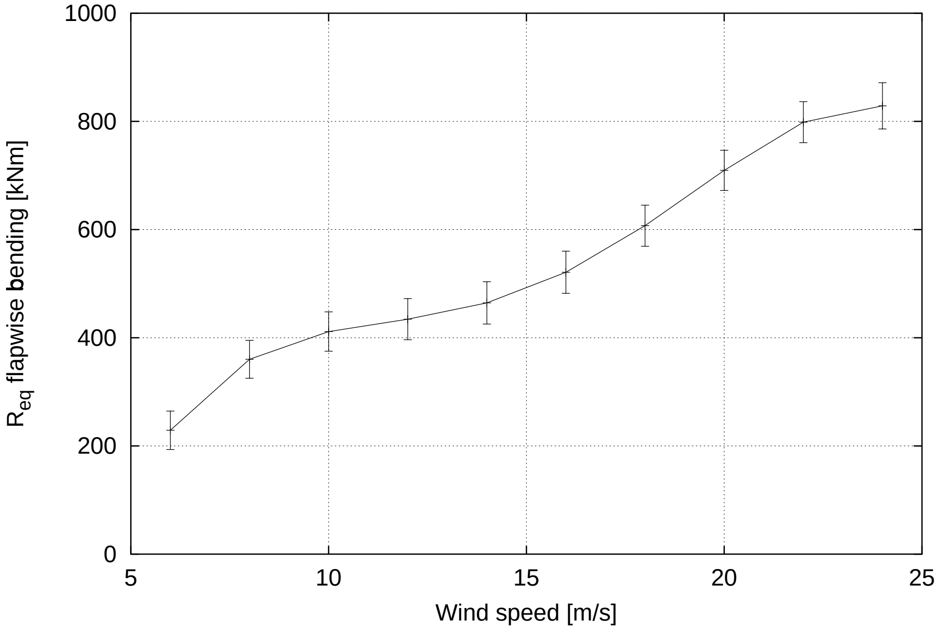

Figure 4. Equivalent load for the flapwise bending moment versus wind speed. The errorbars illustrate $\bar{R}_{\text{eq}} \pm \sigma(R_{\text{eq}})$.

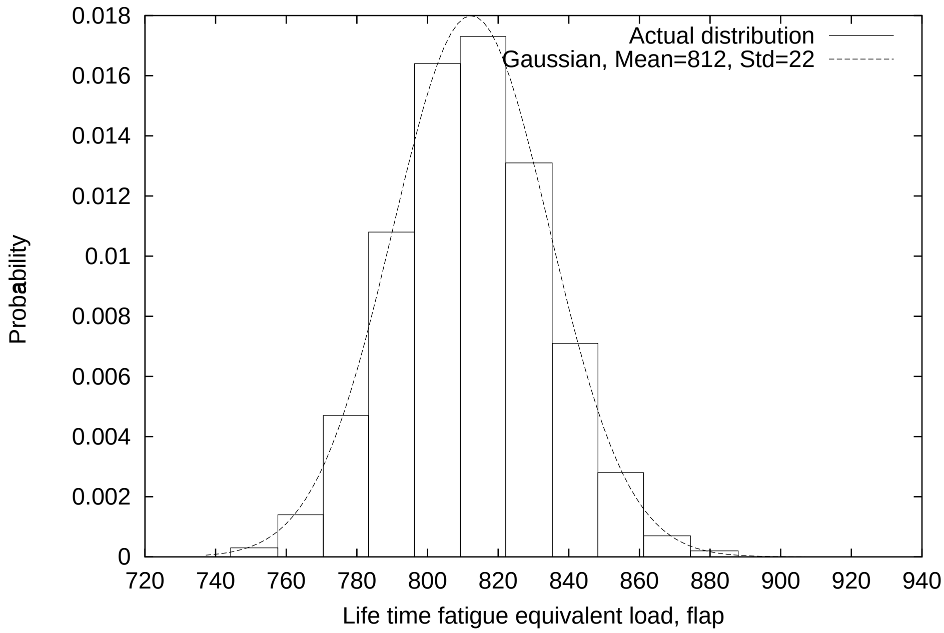

Figure 5. Frequency histogram for life time equivalent flapwise load. Weibull parameters are $A = 10$ m/s and $k = 2.0$.

load is between 0.03 and 0.06 for these load components. Due to the relation between the life time equivalent load and the life time damage, the coefficient of variation of the damage is considerable higher, 0.09-0.33, with the largest value for the flapwise blade bending moment, where the highest Wöhler curve exponent is used.

The contribution to the life time equivalent load and damage depends on the

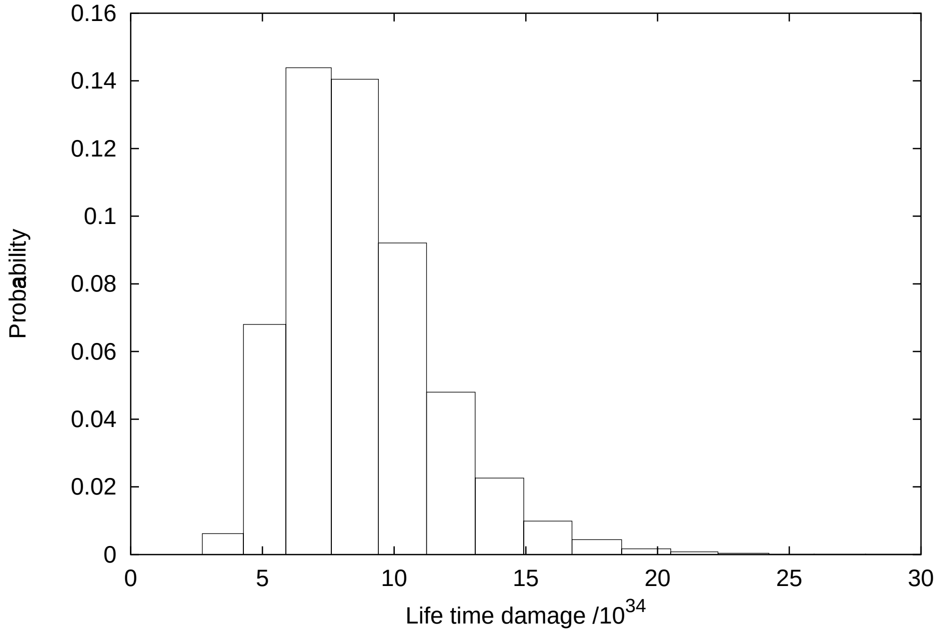

Figure 6. Frequency histogram for flapwise life time damage. Weibull parameters are $A = 10$ m/s and $k = 2.0$.

Table 5. Summary statistics of life time equivalent loads and damage for all load signals. T =600 s, $n_{\mathrm{eq,L}}$=10^7, $m = 3$ for all load signals except flap where $m = 12$. Weibull parameters are $A = 10$ m/s and $k = 2.0$. The damages are normalized by N_{fac}.

-	Flap	Power	Tilt	Yaw	Tow.B.
$\bar{L}_{\mathrm{eq}}$	812.44	712.74	1288.41	1269.28	10292.42
$\sigma(L_{\mathrm{eq}})$	22.10	31.59	39.20	36.38	565.98
$\sigma(L_{\mathrm{eq}})/\bar{L}_{\mathrm{eq}}$	0.03	0.04	0.03	0.03	0.06
N_{fac}	10^{34}	10^7	10^8	10^8	10^{10}
$\bar{D}_L$	8.68	35.47	21.46	20.51	110.09
$\sigma(D_L)$	2.87	4.86	1.96	1.78	18.19
$\sigma(D_L)/\bar{D}_L$	0.33	0.14	0.09	0.09	0.17

mean wind speed. For each wind speed the probability of the wind speed is different and the characteristics (mean and standard deviation) of the equivalent load also differs. Thus, both the average life time load and the variation of the life time load will accumulate different over the wind speeds. The relative contribution to the life time fatigue damage for the i'th wind speed step can be calculated as (cf. Eq. (12)):

$$D_{L,i} = \bar{R}_{\mathrm{eq}}(u_i)^m n_{\mathrm{eq}} p(u_i) n_T / D_L. \tag{13}$$

For all load signals, the relative contribution to the damage is illustrated in Figure 7. For the flapwise blade bending the major part of the fatigue damage occurs at the highest wind speeds (20-24 m/s), while the major part of the damage for the electrical power occurs at the wind speeds between 8 m/s and 16 m/s. For the tilt and yaw load signals, the damage accumulates evenly over the wind speeds, with the highest contribution at 16 m/s. The wind speed range 14 m/s to 24 m/s is the most important for the tower bending moment.

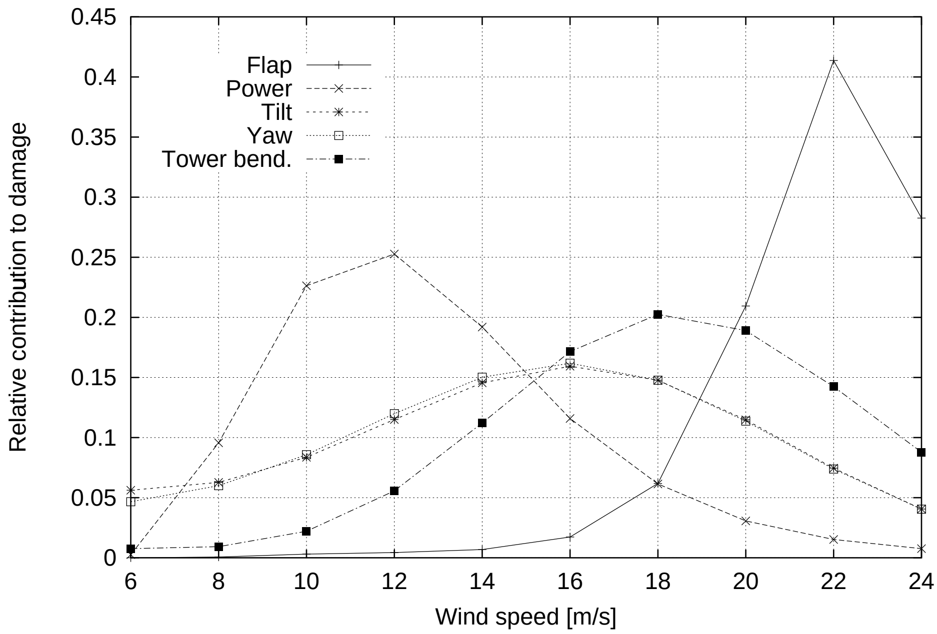

Figure 7. Relative contribution to life time damage for each wind speed.

6 Influence of mean load level

In the previous sections the mean stress level has not been included in the fatigue analysis. It is well-known that the fatigue strength of a material depends on both stress range as well as stress mean level and this can be described by the modified Goodman criterium, [1]:

$$\frac{S_i}{S_f} + \frac{S_m}{S_o} = 1, \tag{14}$$

where S_i is the stress range, S_f is the acceptable stress range from the material Wöhler curve, S_m is the mean stress level and S_o is the static strength. This criterium can be used to modify the original description of the Wöhler curve, Eq. (3) as a general reduction of acceptable stress:

$$\log(S_0 - S_m) - \frac{1}{m}\log N_i = \log S_i. \tag{15}$$

The formulation of the modified equivalent load range is straigthforward (cf. the derivation of Eq. (3) - Eq. (7):

$$D_i = n_i d_i = \frac{n_i S_i^m}{(S_0 - S_m)^m}, \tag{16}$$

where it is assumed that all load ranges for this particular load case have the same mean stress level. This simplified approach is believed to be resonable for the wind turbine loads, which are dominated by the wind load. For the loads considered here, it is beieved to be the case for the flapwise blade bending, the tower bending and the electrical power. The first two of these load signals will be investigated later. It should be noted that the mean load level depends on the actual load case, i.e. $S_m = S_m(U)$.

The total damage can be converted to an equivalent load range $R_{\mathrm{eq,m}}$, which accounts for the mean stress level:

$$R_{\mathrm{eq,m}} = \frac{1}{(M_0 - M_m)}\left(\frac{\sum n_i R_i^m}{n_{\mathrm{eq}}}\right)^{1/m}, \tag{17}$$

where the stress levels S_i have been converted to load ranges R_i (neglecting the moment of resistance). M_i is the mean load level, M_0 is the static strength load. In the derivation of Eq. (9) the S_0 term (here the $M_0 - M_m$ term) was also neglected. Now a factor f_m, which accounts for the correction of the original defined equivalent load ranges compared to the new formulation can be defined:

$$f_m = \frac{R_{\mathrm{eq,m}}}{R_{\mathrm{eq,m}}(S_m = 0)} = \frac{R_{\mathrm{eq,m}}}{R_{\mathrm{eq}}} = \frac{M_0}{M_0 - M_m}. \tag{18}$$

This factor f_m now accounts for the influence of mean stress level and can be multiplied directly with the original defined equivalent load range:

$$R_{\mathrm{eq,m}}(U) = f_m(U) R_{\mathrm{eq}}(U) \tag{19}$$

For each load case it is only necessary to define the mean load level M_m relative to the static strength of the component M_0. The factor should be multiplied on both the mean equivalent load and the standard deviation of the equivalent load at each wind speed in order to account for mean stress effects.

The method is illustrated for the flapwise bending moment in the following. In Figure 8, the mean flapwise load is illustrated versus wind speed. It is now assumed that the maximum mean load ($\approx$ 1000 kNm) corresponds to approximately 1/4 of the static strength, and the factor f_m is calculated from Eq. (18). The factor ranges from approximatelly 1.10 to 1.35 and is also illustrated in Figure 8.

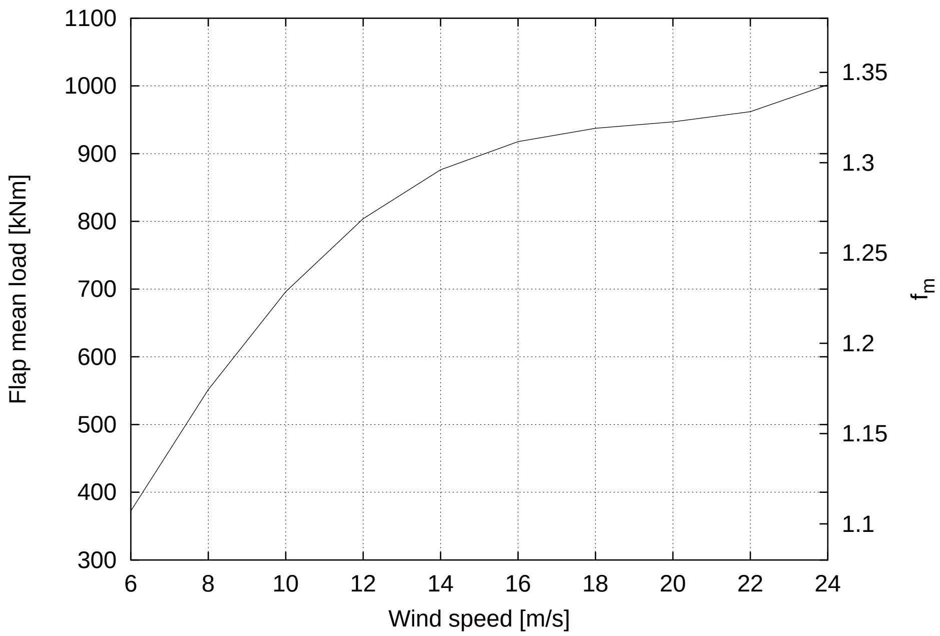

Figure 8. Flapwise mean load versus wind speed and the corresponding value of f_m.

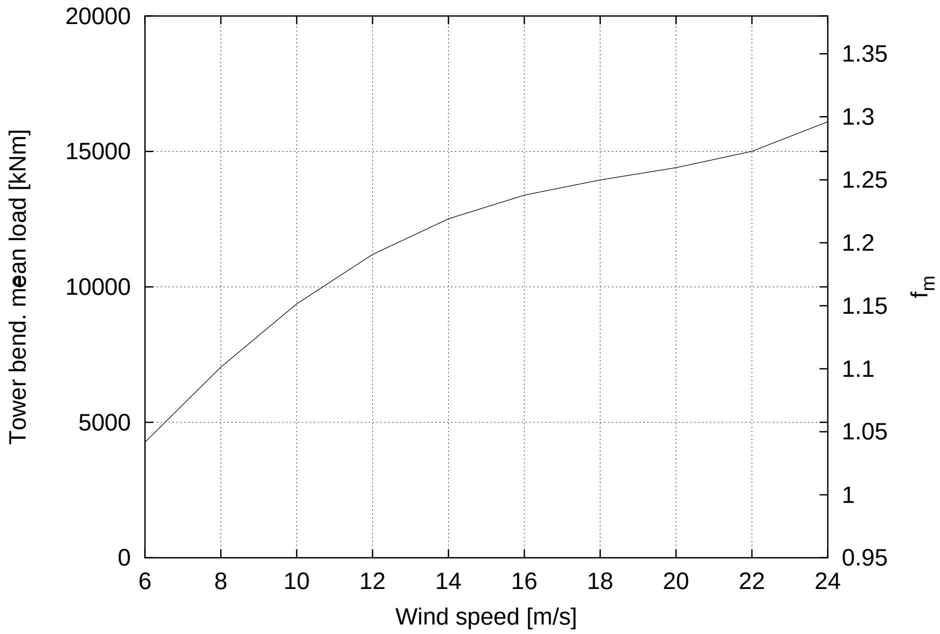

Figure 9. Tower bending mean load versus wind speed and the corresponding value of f_m.

Life time equivalent loads has been calculated for the flapwise bending including mean load effects with the method described in Section 5. The results are given in Table 6, and the first column is identical to the first column of Table 5.

The average life time equivalent load increases 32% and due to the highly non-linear transformation to damage, the life time damage is 28 times higher for the case with mean load effects included. Correspondingly, the life time ($\sim 1/D_L$) is 28 times higher for the case without mean load effects or 28 times lower for the case with mean load included. If a wind turbine blade is designed to a life time of 20 years and the mean load level is ignored then the actual life time will be 0.7 years, assuming that the fatigue load is the design limiting load.

A similar analysis has been carried out for the tower bending moment. The mean load is illustrated in Figure 9 and the results from the life time load analysis in Table 6. In this situation the average life time equivalent load is increased 25% and the life time damage is increased by a factor of 1.94. Thus, for this load signal, the resulting life time is reduced by a factor of 2, when mean load effects are considered. The difference between the increase in life time damage for the flapwise load and the tower bending load is due to the difference in Wöhler curve exponent.

Table 6. Life time equivalent loads and damage for flapwise bending and tower bending with and without mean load effects. T =600 s, $n_{\mathrm{eq,L}}$=10^7, $m = 12$ (flap) and $m = 3$ (tower). Weibull parameters are $A = 10$ m/s and $k = 2.0$. The damages are normalized by $N_{\mathrm{fac}} = 10^{34}$ (flap) and $N_{\mathrm{fac}} = 10^{10}$ (tower).

-	Flapwise bend.			Tower bend.		
-	no mean	with mean	ratio	no mean	with mean	ratio
$\bar{L}_{\mathrm{eq}}$	812.44	1071.34	1.32	10292.42	12833.19	1.25
$\sigma(L_{\mathrm{eq}})$	22.10	29.76	1.34	564.97	719.37	1.27
$\sigma(L_{\mathrm{eq}})/\bar{L}_{\mathrm{eq}}$	0.03	0.03	1.00	0.06	0.06	1.02
$\bar{D}_L$	8.68	240.55	27.71	110.02	213.25	1.94
$\sigma(D_L)$	2.87	82.32	28.68	18.16	35.88	1.98
$\sigma(D_L)/\bar{D}_L$	0.33	0.34	1.03	0.17	0.17	1.02

7 Influence of simulation length

The variation in the life time equivalent load and the life time damage originates from the integration of the variation in the equivalent load at each wind speed. This variation in equivalent load depends on several parameters, among others the length of each simulation. In the previous sections, all results are based on simulations length $T = 600$ seconds at each wind speed, but often a simulation length of $T = 300$ seconds are used in industrial applications. The influence of the reduced simulation length is investigated in this section.

For three wind speeds (10, 15 and 20 m/s) the characteristics of the equivalent loads for $T = 300$ s are identified in a similar way as previously. The summary statistics are given in Table 7 and in Table 8 the ratio of the values for $T = 300$ s and $T = 600$ s are given.

Table 7. Summary statistics of equivalent load ranges for all load signals. $T = 300$ s, $n_{\text{eq}} = 300$, $m = 3$ for all load signals except flap where $m = 12$.

U	-	Flap	Power	Tilt	Yaw	Tow.B.
m/s		kNm	kW	kNm	kNm	kNm
10	$\bar{R}_{\text{eq}}$	405.24	214.74	311.76	304.47	1489.72
	$\sigma(R_{\text{eq}})$	60.15	33.88	55.95	54.48	279.71
	v_r	0.15	0.16	0.18	0.18	0.19
15	$\bar{R}_{\text{eq}}$	490.86	247.24	420.11	422.78	3212.19
	$\sigma(R_{\text{eq}})$	45.02	29.81	47.54	45.11	579.65
	v_r	0.09	0.12	0.11	0.11	0.18
20	$\bar{R}_{\text{eq}}$	714.10	232.45	671.79	657.04	6016.33
	$\sigma(R_{\text{eq}})$	53.02	18.32	52.42	48.53	1170.03
	v_r	0.07	0.08	0.08	0.07	0.19

Table 8. Ratio of equivalent load ranges for all load signals for $T = 300$ s and $T = 600$ s, $m = 3$ for all load signals except flap where $m = 12$.

U	-	Flap	Power	Tilt	Yaw	Tow.B.
m/s		kNm	kW	kNm	kNm	kNm
10	$\bar{R}_{\text{eq}}$	0.98	1.05	1.07	1.07	0.99
	$\sigma(R_{\text{eq}})$	1.65	1.41	1.48	1.49	1.83
	v_r	1.68	1.35	1.38	1.40	1.85
15	$\bar{R}_{\text{eq}}$	1.00	1.04	1.04	1.04	1.02
	$\sigma(R_{\text{eq}})$	1.15	1.43	1.38	1.43	1.38
	v_r	1.14	1.34	1.26	1.33	1.39
20	$\bar{R}_{\text{eq}}$	1.01	1.03	1.03	1.03	0.99
	$\sigma(R_{\text{eq}})$	1.43	1.49	1.54	1.53	1.29
	v_r	1.42	1.45	1.50	1.49	1.30

The mean value of the equivalent is only moderatly influenced by the simulation length. The largest difference between $T = 300$ s and $T = 600$ s is 7% and for the main part of the loads and wind speeds, the average of the equivalent load from the low simulation length is highest. The standard deviation of the equivalent load is increased between 15% and 83%.

Another important parameter is the number of load simulations used for each wind speed. In the previous investigations, only one simulations is used at each wind speed. If a higher number of simulations are averaged at each wind speed, the variation can be reduced. The averaging must be a damage-averaging in order to take the non-linear features of the equivalent load into account.

The differences in statistics for different time simulation length and for different number of simulations for each wind speed (with the difference in standard deviation as the most important) will influence the life time loads and life time damage. Following the methods described in Section 5, the influence has been analysed for two load signals, the flapwise bending and the tilt moment.

Table 9. Mean value of life time fatigue loads for flapwise bending and tilt moment.

	Flap		Tilt	
	$T = 300$ s	$T = 600$ s	$T = 300$ s	$T = 600$ s
$\bar{L}_{\text{eq}}$	823.81	812.44	1364.63	1288.41
$\bar{D}_L$	$10.25 \cdot 10^{34}$	$8.68 \cdot 10^{34}$	$25.46 \cdot 10^{8}$	$21.46 \cdot 10^{8}$

The average life time equivalent load and damage are not dependend on the number of load simulations used for each wind speed, due to the damage-averaging at each wind speed. For the case with $T = 300$ s the life time equivalent load is increased approximatelly 3% compared to the case with $T = 600$ s (given in Table 9). The average life time damage is increased 18%.

Table 10. Standard deviation of life time fatigue loads for flapwise bending and tilt moment. Flapwise damage normalized by 10^{34} *and tilt damage normalized by* 10^{8}.

		Flap		Tilt	
		$T = 300$ s	$T = 600$ s	$T = 300$ s	$T = 600$ s
n=1	$\sigma(L_{\text{eq}})$	31.37	22.10	57.84	39.20
	$\sigma(D_L)$	4.97	2.87	3.25	1.96
n=2	$\sigma(L_{\text{eq}})$	22.86	15.89	40.78	27.61
	$\sigma(D_L)$	3.56	2.07	2.28	1.38
n=3	$\sigma(L_{\text{eq}})$	18.80	13.00	33.46	22.64
	$\sigma(D_L)$	2.88	1.68	1.87	1.13
n=4	$\sigma(L_{\text{eq}})$	16.56	11.40	29.01	19.64
	$\sigma(D_L)$	2.53	1.47	1.62	0.98
n=5	$\sigma(L_{\text{eq}})$	14.86	10.21	25.95	17.56
	$\sigma(D_L)$	2.26	1.32	1.45	0.88
n=6	$\sigma(L_{\text{eq}})$	13.58	9.31	23.74	16.06
	$\sigma(D_L)$	2.06	1.20	1.33	0.80

The standard deviation of both life time equivalent load and life time damage is increased approximatelly 40%. The coefficient of variation as a function of number of simulations is illustrated in Figures 10-11. Note that the same coefficient of variation can be obtained for $T = 300$ s as for $T = 600$ s if the number of simulations is the double. This indicates that the variation of life time equivalent load and life time damage relates to the statistical material used.

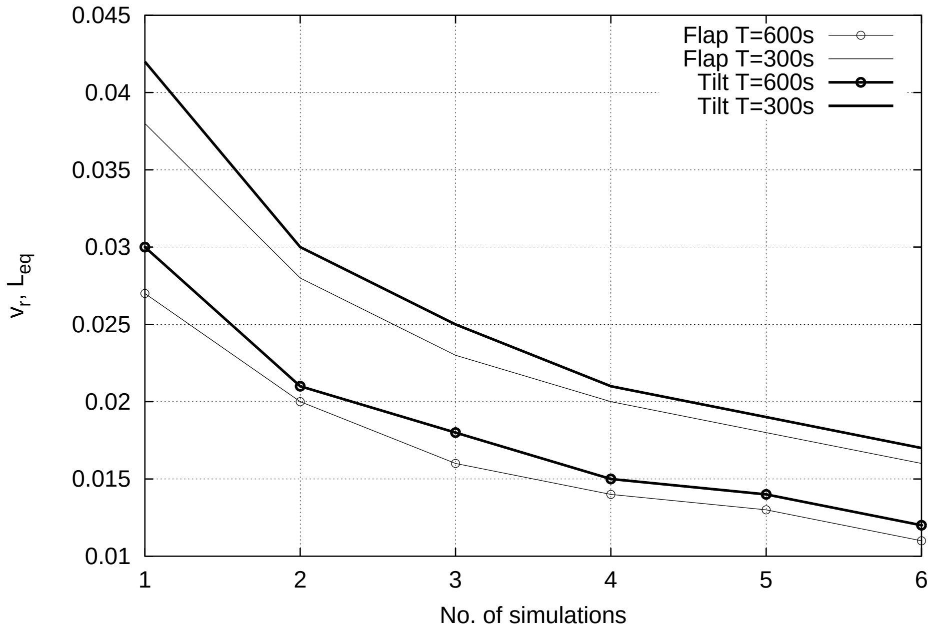

Figure 10. Coefficient of variation of life time equivalent load versus number of simulations. Simulation length as parameter.

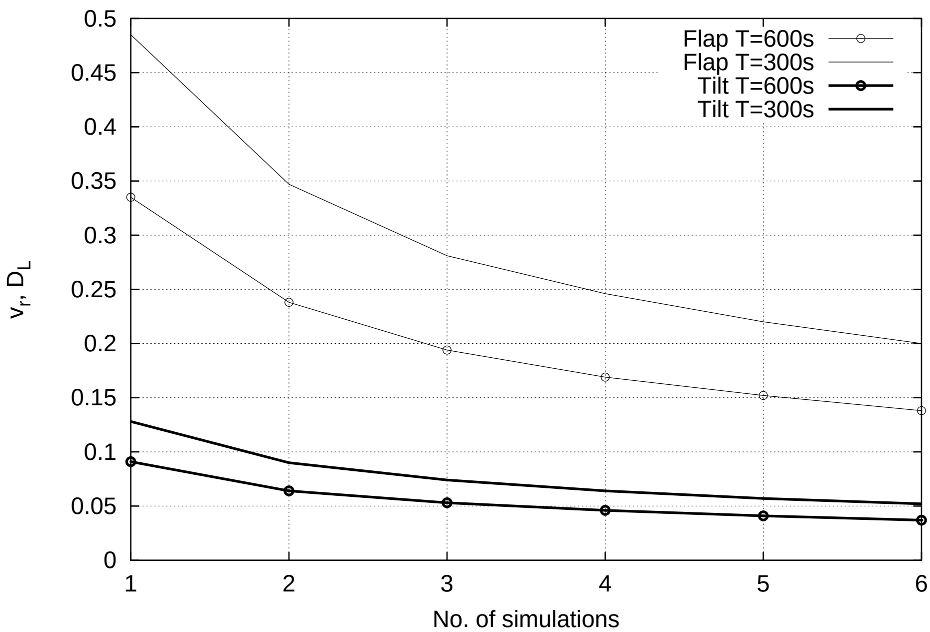

Figure 11. Coefficient of variation of life time damage versus number of simulations. Simulation length as parameter.

8 Influence of turbulence intensity

The influence of turbulence intensity on the fatigue equivalent load range has been investigated at four wind speeds, 7 m/s, 10 m/s, 15 m/s and 20 m/s and at three levels of turbulence intensity, 0.10, 0.15 and 0.20. At all combinations of these parameters, the approach described in Section 4 has been followed and the statistics of the equivalent moment has been identified ($\bar{R}_{\mathrm{eq}}$ and $\sigma(R_{\mathrm{eq}})$). The results are illustrated in Figures 12 -16. For all load components it is seen that an increase of the turbulence intensity by a factor of 2 results in a similar increase in the equivalent load range (a factor of 2). This also holds for the standard deviation of the equivalent load range.

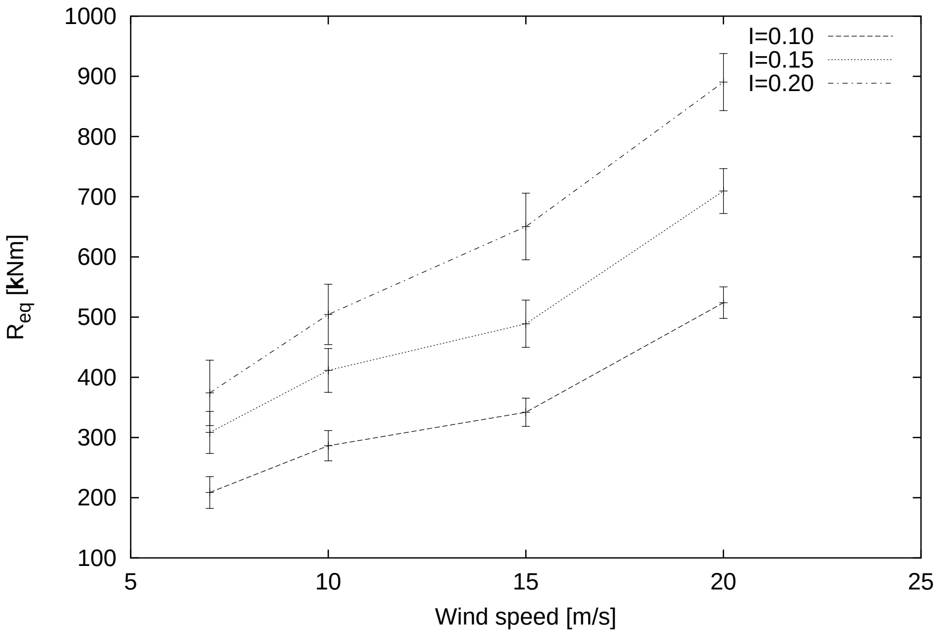

Figure 12. Equivalent load for flapwise moment at different levels of turbulence intensity. The errorbars illustrate $\bar{R}_{\mathrm{eq}} \pm \sigma(R_{\mathrm{eq}})$.

Furthermore, the influence of turbulence intensity on the life time equivalent load and damage has been investigated using the approach described in Section 5. These results are illustrated in Figures 17 - 21. The sensitivity of the life time equivalent load range corresponds to the equivalent load range at each wind speed. Thus, an increase of a factor of 2 of the turbulence intensity corresponds to an increase of a factor of 2 of the life time equivalent load range. Due to the non-linear relation between the life time equivalent load range and the life time damage, the sensitivity of life time damage to turbulence intensity is different. For this parameter, an increase of the turbulence intensity by a factor of 2 results in an increase by a factor of 2^m. This means that the sensitivity to turbulence is significantly different for the life time damage of the different load components.

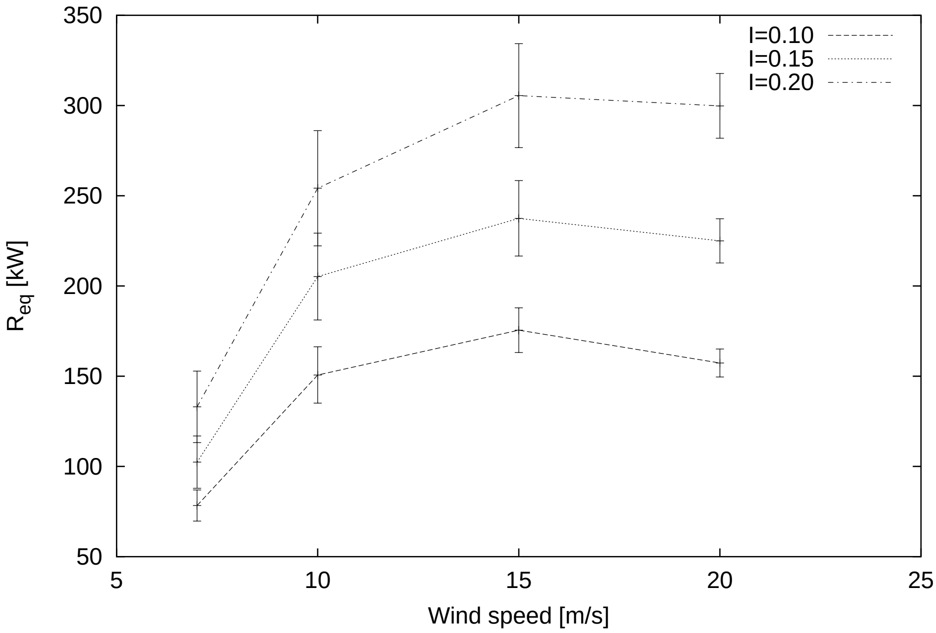

Figure 13. Equivalent load for electrical power at different levels of turbulence intensity.

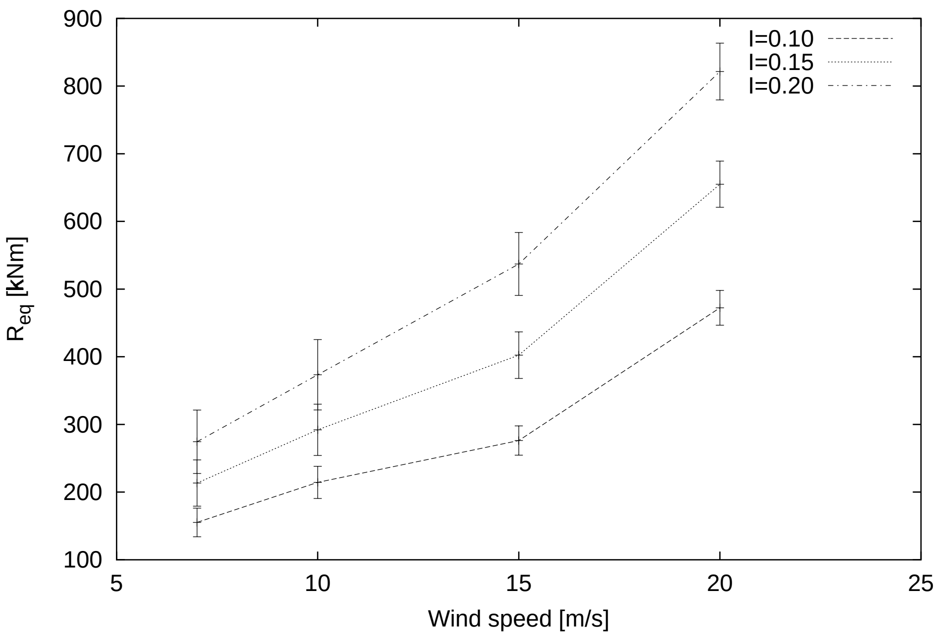

Figure 14. Equivalent load for tilt moment at different levels of turbulence intensity.

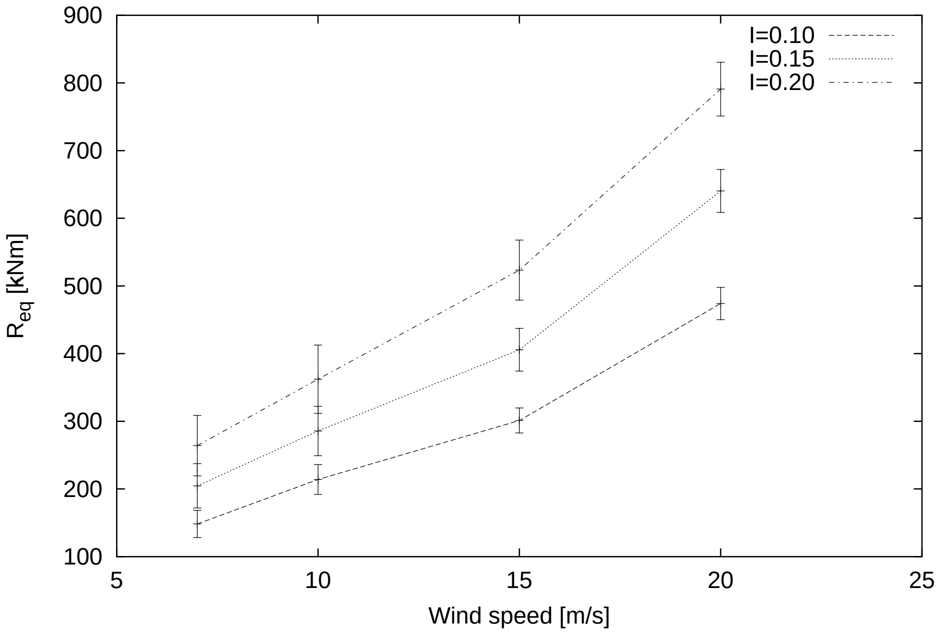

Figure 15. Equivalent load for yaw moment at different levels of turbulence intensity.

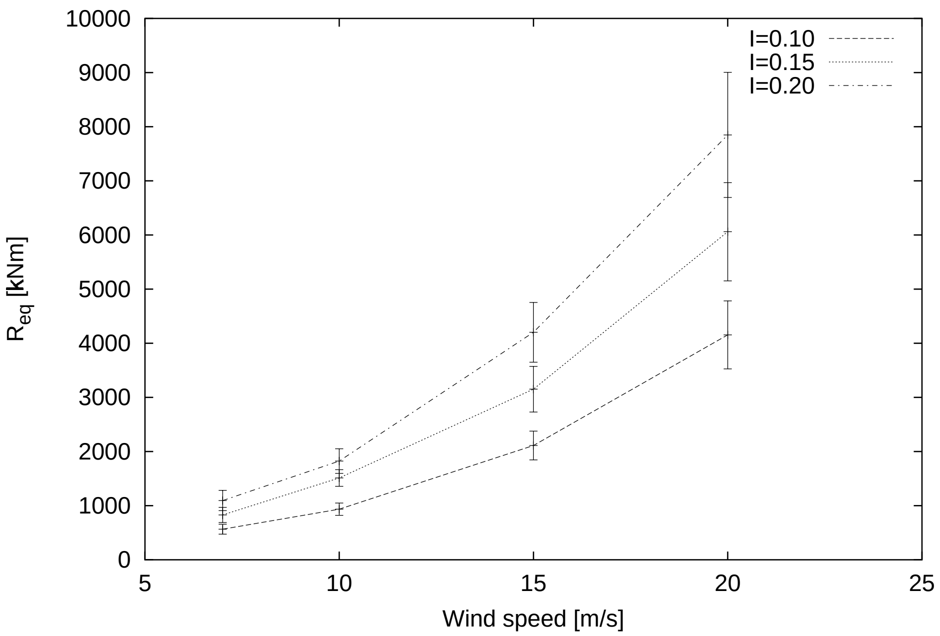

Figure 16. Equivalent load for tower bending moment at different levels of turbulence intensity.

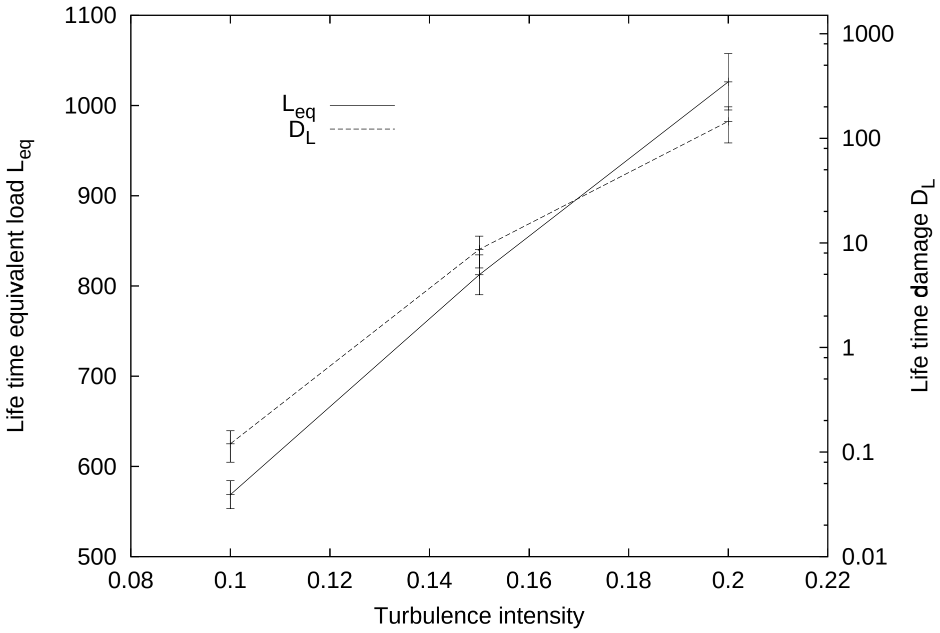

Figure 17. Life time equivalent load and damage for flapwise bending moment at different levels of turbulence intensity. Note that the damage axis is logarithmic.

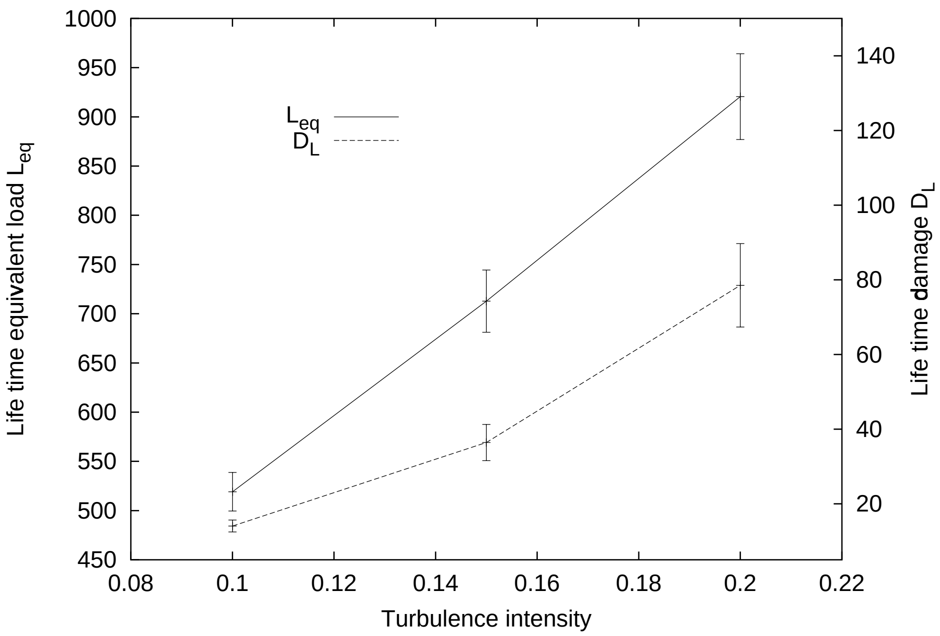

Figure 18. Life time equivalent load and damage for electrical power at different levels of turbulence intensity.

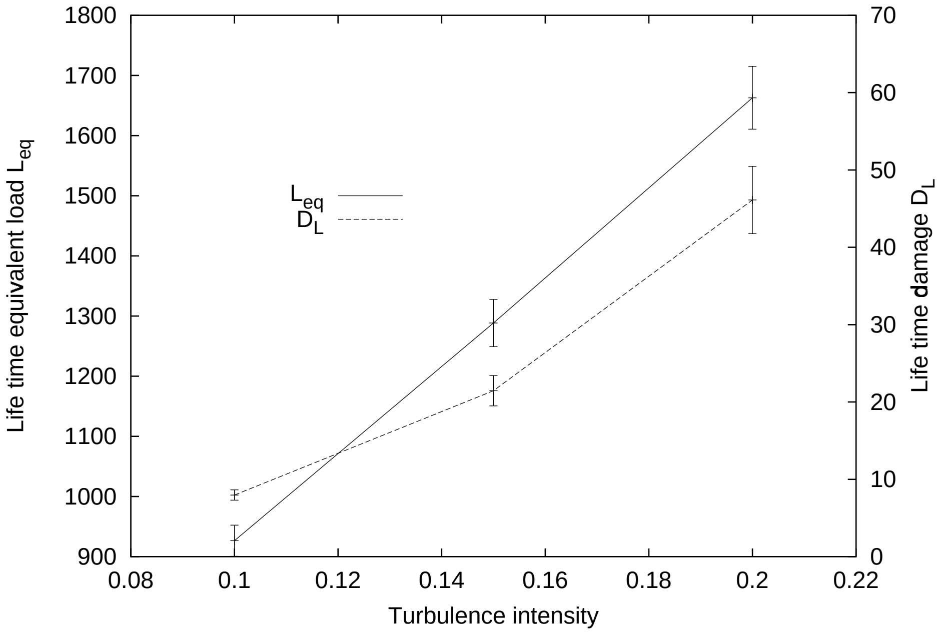

Figure 19. Life time equivalent load and damage for tilt bending moment at different levels of turbulence intensity.

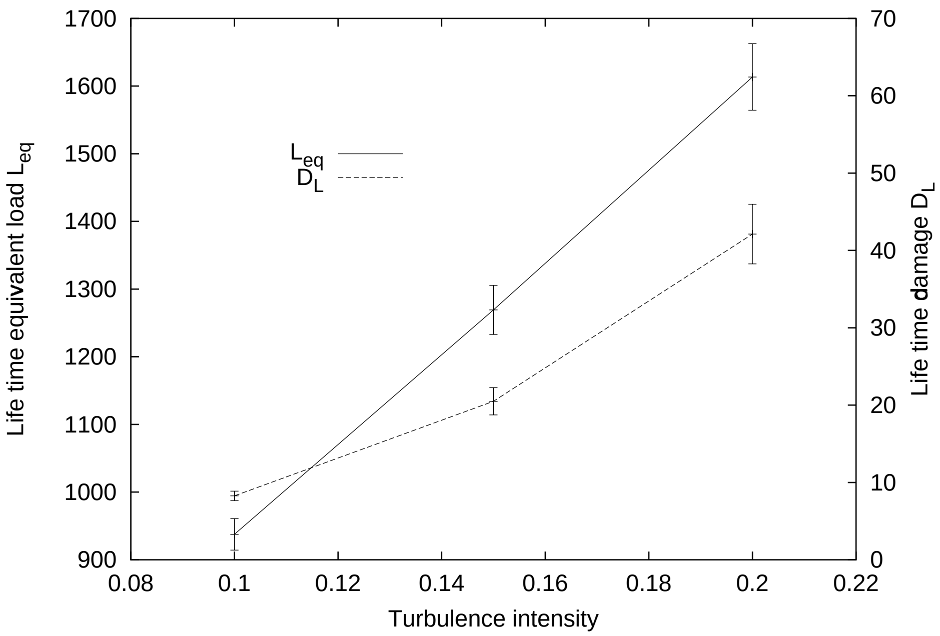

Figure 20. Life time equivalent load and damage for yaw bending moment at different levels of turbulence intensity.

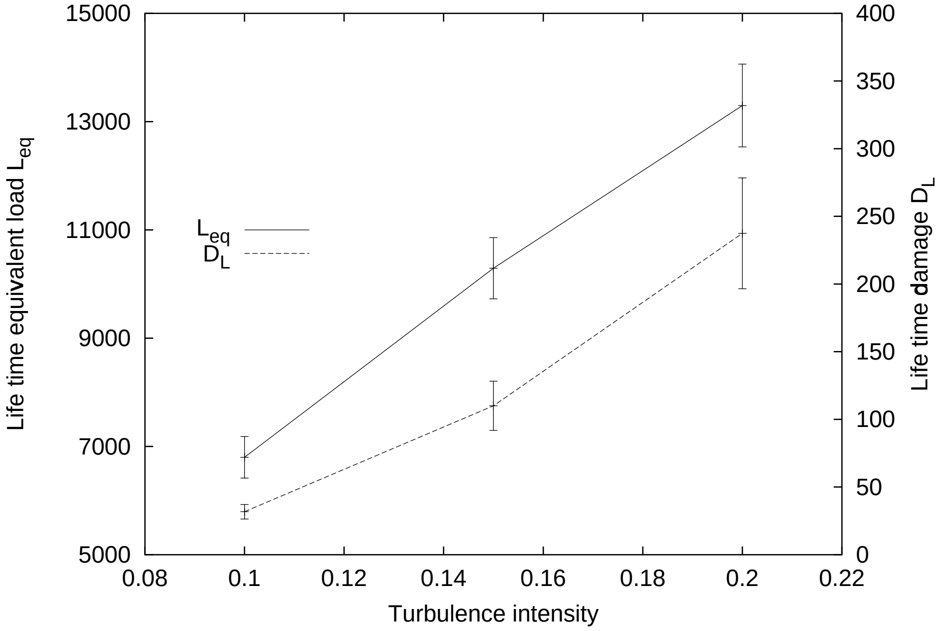

Figure 21. Life time equivalent load and damage for tower bending moment at different levels of turbulence intensity.

9 Uncertainty of life time loads

In the previous sections, the statistical characteristics of life time fatigue loads has been investigated for several different simulation parameters (i.e. simulation length, mean value, turbulence intensity). In this section, these results are summarized and illustrated in general terms.

If the standard deviation of the life time equivalent load $\sigma(L_{\text{eq}})$ is known, a confidence interval of the estimated mean value of the life time equivalent load $\bar{L}_{\text{eq}}$ can be calculated as $\pm 1.96\sigma(L_{\text{eq}})/\sqrt{n}$ where n is the number of realizations of the life time equivalent load. A confidence level of 95% has been chosen. Thus, assuming that the calculated standard deviations of the life time equivalent loads (Table 5) represent the true standard deviation, this confidence interval can be estimated.

Using the methods in Section 5, the life time equivalent loads can be calculated in two different ways:

- Using the same seed value at each wind speed
- Using different seed values at each wind speed

All previous results have been calculated using the latter method, and it is obvious that the variation in the life time equivalent load is reduced (averaged out) compared to the other method.

For both method, the 95% confidence intervals have been calculated for the different load components, Figure 22 and 23. The ordinate values are the normalized confidence interval range, i.e. two times $\pm 1.96\sigma(L_{\text{eq}})/\sqrt{n}$ divided by the actual mean value of the life time equivalent load.

For a given target uncertainty of the life time equivalent load, the necessary number of simulations (at each wind speed) can be determined from these figures. As an example, if the target uncertainty is $\pm$ 5% ($\sim$ 0.1 in the figures), the necessary number of simulations is 5 if different seed values for each wind speed are used. On the other hand, if the same seed value is used at each wind speed, the necessary number of simulations is more than 20.

The results in Figure 22 and 23 are all based on a turbulence intensity of $I = 0.15$, a simulation length of $T = 600$ s and Weibull parameters of $A = 10$ m/s and $k = 2.0$. For other values of simulation parameters the results for the flapwise load are given in Figure 24. The most important difference is that a smaller simulation length ($T = 300$ s) results in a significantly increased uncertainty. This corresponds well with the results in Section 7.

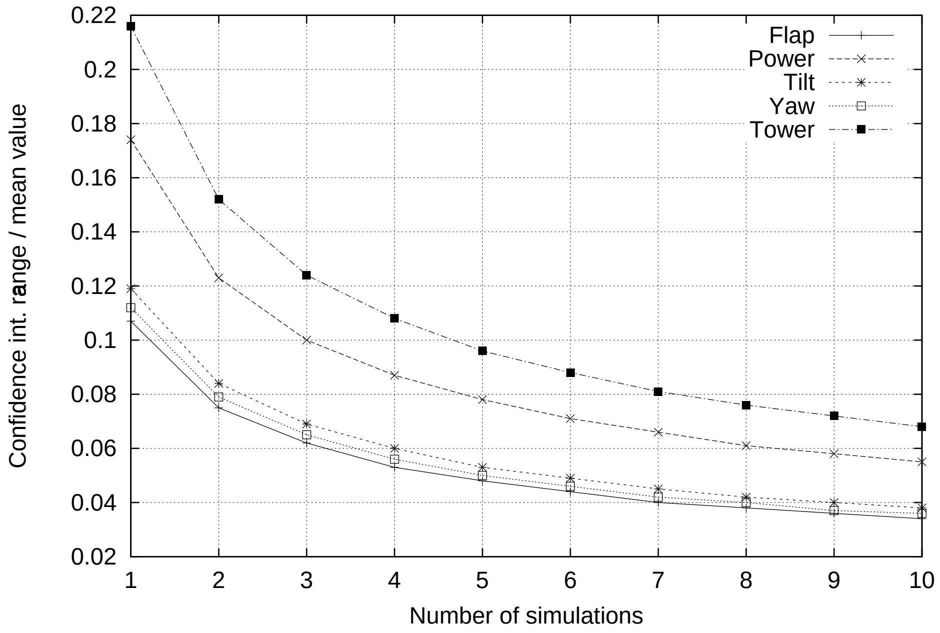

Figure 22. Normalized 95 % Confidence interval range of life time equivalent loads. Different seed values at each wind speed.

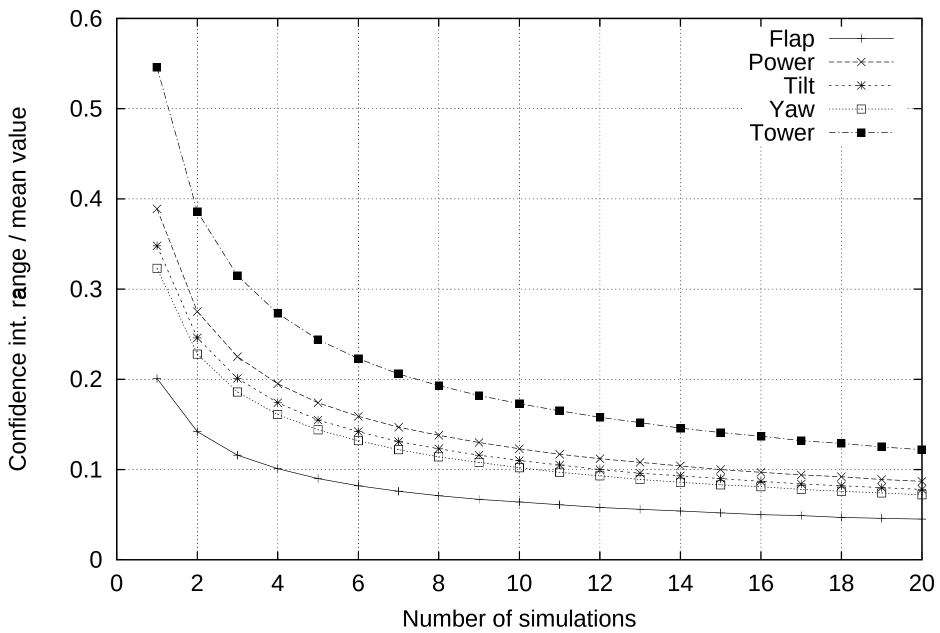

Figure 23. Normalized 95 % Confidence interval range of life time equivalent loads. Same seed values at each wind speed.

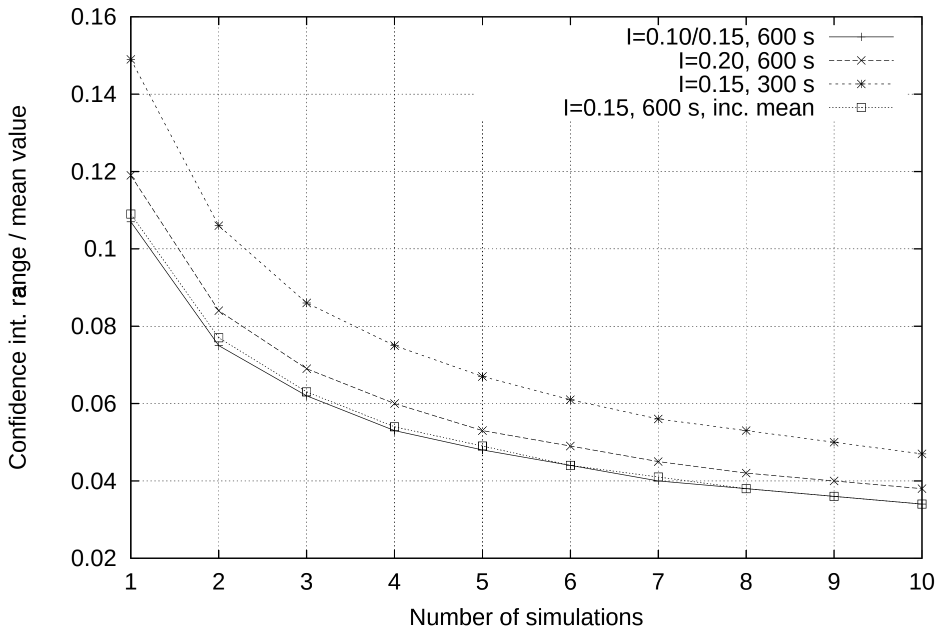

Figure 24. Normalized 95 % Confidence interval range of life time equivalent flapwise loads. Different seed values at each wind speed.

10 Conclusions

The investigation has revealed several characteristics of the fatigue equivalent load and fatigue damage of wind turbine load signals.

It is evident, that the distributional function of the equivalent loads tends to be Gaussian. At the lower wind speeds, the typical coefficient of variation is 0.15, while at higher wind speeds it is 0.05. For the tower bending moment, the coefficient of variation seems to be constant $\approx$0.13 for all wind speeds.

Also the accumulated life time equivalent load range seems to be Gaussian distributed. For this quantity, the typical coefficient of variation is 0.05.

Concerning the fatigue damage at each wind speed and the accumulated life time fatigue damage, neither of these quantities are Gaussian distributed. This corresponds well with the non-linear transformation of the Gaussian distributed equivalent load range and life time equivalent load range.

The low values of the coefficients of correlation between the equivalent load range of the different load components illustrates that it is not always possible to use a 'typical' set of turbulence time series (seed values) to obtain the correct damage-averaged load time series for all load components. In some cases there seems to be no alternative to use several different turbulence time series.

The relative distribution of fatigue damage differs for different load components. For the flapwise load, the majority of damage accumulates at the highest wind speeds. For the other load components lower wind speeds are of relatively more importance.

For the flapwise blade bending moment and for the tower root bending moment, the influence of mean load level on the fatigue has been illustrated using a somewhat simplified approach. It is obvious that this analysis only applies to the relevant parts of the construction, e.g. not to welded parts of the tower. For both load signals, the mean load level seems to be very important. When mean load levels are taken into account, the life time equivalent load range increases 25-35%, causing the life time damage to increase by a factor of 2 (tower bending) and 28 (flapwise bending), respectively. It is thus concluded, that the mean load levels must be taken into account.

The length of the simulations changes both the fatigue damage and the variation of the fatigue damage. In the actual investigation, the turbulence intensity was fixed, causing the wind speed time series for a shorter simulation length ($T = 300$s) to include more high frequency energy than time series for longer simulation length ($T = 600$s). This causes a slightly higher fatigue impact for the shorter simulation length. The standard deviation of life time fatigue loads based on $T = 300$ s time series is increased by a factor of 1.2-1.8 compared to the standard deviation of life time fatigue loads based on $T = 600$ s time series. One possibility of reducing the standard deviation is to average several simulations at each wind speed. The results illustrate that the coefficient of variation of $2n$ $T = 300$ s simulations is the same as n $T = 600$ s simulations.

Turbulence intensity is a very important parameter for the fatigue loads. The investigations shows, that a doubling of the turbulence intensity causes a doubling of the fatigue equivalent load for all wind speeds. Furthermore, the standard deviation of the fatigue equivalent load doubles, causing the coefficient of variation to be unaffected. Similarily, the life time equivalent load increases by a factor of 2 if the turbulence intensity is increased by a factor of 2, and the same holds for the standard deviation of the life time equivalent load. For the life time damage, both the mean value and standard deviation changes by a factor of 2^m when the turbulence intensity changes a factor of 2.

The uncertainty of the life time equivalent loads has been calculated as a confidence interval on the mean estimate. From this analysis, the necessary number of simulations for a given target uncertainty can be obtained directly. An important result is that the uncertainty of the life time equivalent load is significantly higher if the same seed values are used at all wind speeds compared to the uncertainty obtained with different seed values at each wind speed. Thus, different seed values should be used at different wind speeds.

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Abstract (Max. 2000 char.)

The objective of the present investigation is to quantify the statistical variation associated with fatigue loads for wind turbines. Based on aeroelastic calculations for a 1.5 MW stall regulated wind turbine, the variation is quantified, and parameters of importance for the statistical variation are investigated.
The results illustrate that the coefficient of variation of the life time equivalent load range, for typical wind turbine load components, is of the order of magnitude 5%. This result is based on one 10 minute simulation for each of 10 wind speed intervals between 5 and 25 m/s. It is shown that the effect of mean stress level is of major importance in fatigue analysis. Furthermore, the influence of simulation length and turbulence intensity is illustrated. Finally, an estimate of the uncertainty of the life time equivalent loads is given in general terms.

Descriptors INIS/EDB

FATIGUE; HORIZONTAL AXIS TURBINES; SERVICE LIFE; STOCHASTIC PROCESSES; WIND LOADS

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